SPE
Society of Petroleum Engineers

SPE 14504

A Systematic Approach for Economic Development of the Devonian Shale Gas Resources

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Abstract

The unconventional reservoirs in the Devonian Shales are considered to be the most underdeveloped and potentially the most productive source of natural gas in the Appalachian Basin. The identification of high potential areas for exploration and development of Devonian Shale formations with respect to economic production of natural gas is becoming increasingly difficult. During the past two years, the gas produced from the Devonian Shale horizons has encountered additional difficulties in remaining competitive due to the declining demand and gas supply surplus. For Devonian Shale resources to remain competitive and regain the market, it is necessary to reduce the cost of exploration, drilling and production. It must further be recognized that the development of the Devonian Shale gas resources is limited not only by existing engineering technology but also by the identification of prospective areas where the technology can be successfully applied. It is, therefore, essential that target areas for shale development be selected based upon sound exploration rationales.

One economic means of exploiting the Devonian Shale is through multiple completion in conjunction with shallow gas-bearing formations which are stratigraphically located above the shale horizons. The overall objective of this study is to delineate, assess and evaluate areas which are potential candidates for multiple completion in the Devonian Shale formations as well as shallower gas-bearing horizons (such as Big Injun, Weir, Berea, and Big Lime) in West Virginia. The reservoir parameters such as porosity, gas saturation, net formation thickness, open flow potential, and production data have been collected and analyzed to identify and evaluate high potential areas for the mentioned formations. The qualitative and quantitative interpretations of data and assessment of areas for future development have been enhanced by computer generated maps. These maps provide interregional comparison as well as a guide for future optimization of stimulation treatments. The identification of potential areas amenable to multiple completion has been achieved by superimposition of the generated maps of Devonian Shale and other gas-bearing horizons.

References and illustrations at end of paper.

Introduction

The unconventional reservoirs in the Devonian Shales are considered to be the most underdeveloped and potentially the most productive source of natural gas in the Northeastern United States[1]. The hydrocarbon bearing shale formations underlie an area of approximately 90,000 square miles in the Appalachian Basin[2]. Up to 400 trillion cubic feet of natural gas are estimated to be contained in the fractures and matrices of these rocks, but only a small percentage is currently being recovered.

The Devonian Shale reservoirs are characterized by permeabilities insufficient to allow economic production through conventional completion techniques. It is widely recognized that proven gas reserves in the Appalachian Basin would be substantially increased if Devonian Shale gas resources could be developed more economically. Difficulties in reservoir characterization, prediction of responsiveness of the formation to stimulation treatments, and determination of production mechanisms are among the major problems which have hindered the economical development of Devonian Shale reservoirs. The previous research and development tasks have identified several major areas which require additional research for technology development as related to economic exploitation of the shale hydrocarbon resources. However, it must be pointed out that the development of the Devonian Shale is limited not only by existing technology but also by the identification of prospective areas where the technology can be successfully applied[3].

The assessment and identification of high potential areas for exploration and development of Devonian Shale reservoirs with respect to economic production of natural gas is becoming increasingly difficult. Such exploration activities are considered high risk ventures, thus, discouraging the continuous exploitation of the Devonian Shale natural gas resources.

Multiple completion, or commingled production, is a cost-effective and economic means to exploit the Devonian Shale while simultaneously producing natural gas from other horizons through a common well-bore[3]. Therefore, the delineation of areas which are potential candidates for multiple completion in Devonian Shale formations, as well as other gas-bearing horizons which are stratigraphically located above the shale members, will provide a sound rationale for future development of the shale reservoirs in West Virginia[4].

Geological Background

The formations under study include: Big Lime, Big Injun, Weir, Berea, and the Devonian Shale horizons. A brief geological description of the above mentioned units follows:

A. Devonian Shale:

One of the most distinctive and well-known stratigraphic intervals within the Appalachian Basin is the thick shale sequence referred to by drillers as the "Devonian Shales". In West Virginia the interval known as the "Devonian Shale" refers to all fine-grained clastic rocks between the top of the Middle Devonian Onondaga Limestone (and its facies equivalent, the Huntersville Chert) and the base of the Lower Mississippian Berea Sandstone. "Devonian Shale" correctly applies only to the shales in the western one-third of the state, where various sandstones and siltstones of the Hampshire and Chemung formations are not present to subdivide the shales. Although the term "brown shales" is often used as a synonym of the Devonian Shales, it is more accurately restricted to the darker shales within the thick sequence[5].

The Devonian Shales in the subsurface of West Virginia occupy the same stratigraphic position as 6 clastic formations in the eastern outcrop: the black Marcellus shale; Mahantango (Hamilton) siltstones and shales; the second black to dark gray Harrell, which contains the Tully Limestone Member near its base; the Brailler siltstones and shales, some black; the greenish-gray, and brown Chemung sandstones, siltstones, and shales; and the Hampshire (Catskill) redbeds. Throughout the state the thickness of the entire Devonian clastic sequence ranges from less than 1000 feet in the southwestern gas fields to more than 7000 feet in the north-central subsurface, and up to 10,500 feet in the eastern outcrops[5]. In the western subsurface the sequence is composed of repetitive cycles of interbedded shales, silty-shales, and siltstones[5,6,7]. Each cycle consists of a basal black, organic-rich shale overlain by a lighter gray to green, frequently siltier shale or siltstone. Because of the high uranium content and low specific gravity (low bulk density) associated with organics, the black shale units show prominently on geophysical logs and provide the basis for stratigraphic subdivisions. Eastward the cyclic nature of the shales is not preserved, and the unit undergoes a facies change to coarser clastics[5,6]. Because of the facies changes, transitional boundaries, and the lack of recognizable key beds, nomenclature from the eastern outcrop cannot be applied to the subsurface in West Virginia. In western West Virginia, the lower part of the cyclic shale sequence were correlated with similar sequences of the Hamilton Group and the Genesee, Sonyea, West Falls, and Java formations in New York[6,7]. The upper portion of the shale has been correlated with the black Ohio Shale formation of Ohio.

Gas production throughout western West Virginia is from the dark-gray to black, organic-rich brown shales. In the western counties gas is produced from several shale zones, often from dark shales immediately below the gray shales. In north-central West Virginia, where the sequence becomes more clastic, gas is produced from 20 informally names Upper Devonian Hampshire (Catskill) and Chemung sandstones, and few wells are drilled entirely through the shale sequence. The entire shale sequence thickens eastward across the state and the thickness of the dark shales increases, but they occupy a smaller percentage of the stratigraphic section and occur at greater depths. In western counties the dark shales makeup 60 percent (300 feet) of the seuqence, whereas in Kanawha County the black shales thicken to 1000 feet, but represent only 16 to 20 percent of the sequence[5].

The principal producing units in the shales are the Huron Member of the Ohio Shale, and the Rhinestreet Shale Member of the West Falls formation. Other producing units include the Genesee and Marcellus formations, and siltstone tongues of the Java formation, which includes drillers' Riley, Benson, and Alexander sands. Production appears to be stratigraphically controlled. Production decreases eastward as the dark shales undergo a facies change to greenish-gray lighter shales, and gas shows are often noted immediately below the gray shales which may be acting as a permeability barrier to gas migration[7].

Although black shales are fairly common in the geologic record, the origin of the Devonian Shale sequence of the Appalachian Basn is still uncertain and controversial. Basically, there are two schools of thought regarding the origin of these shales: one suggests a shallow water origin, and the other suggests a deep water origin. A very complex and interrelated combination of processes and environments, such as mountain building alternating with periods of quiescence, position of the highlands, high organic productivity, tropical climate, and a restricted marine basin with little clastic influx were responsible for Devonian Shale deposition.

B. Big Injun:

The Lower to Middle Mississippian "Big Injun" producing horizons in West Virginia consist of several lithologies of different depositional environments, stratigraphic position, and geographic areas. Compounding this problem is the multiple usage of the term "Big Injun" for both the Lower Mississippian Pocono sandstones, siltstones, and shales and the Middle Mississippian siliceous, oolitic limestones and dolomites of the basal Greenbrier Group.

The Lower Mississippian Pocono Group consists of lensing and interfingering sandstones, siltstones, and shales. This high lateral variability is caused by rapid lateral facies changes characteristic of fluvial and deltaic environments, and makes subsurface correlations extremely difficult. The term "Pocono Big Injun" is usually confined to the sandstone units of the uppermost Pocono Group lying below the Maccrady formation. However, locally productive sandstone lenses at the base of the Pocono, termed "Squaw" by drillers, are sometimes included within the "Pocono Big Injun" sandstones.

In north and northwestern West Virginia the Pocono Big Injun sandstone is a light gray subgraywacke (lithic arenite), fine to medium-grained with conglomeratic streaks[8,9]. It is regionally extensive and has been correlated with the Logan sandstone of Ohio, the Burgoon sandstone of Pennsylvania, and the Bradford sandstone of Virginia[8,10]. The sandstone is highly productive of both oil and gas in this area and production extends into Pennsylvania.

In southern West Virginia the Pocono Big Injun is a relatively massive sandstone present near the top of the Pocono Group. In Wayne and Lincoln Counties it ranges from 0 to 200 feet in thickness, is underlain by a series of gray to green siltstones and shales[11] and is overlain by the redbeds of the Maccrady formation. However, locally the Maccrady and Pocono Big Injun sandstones are missing in southern West Virginia.

In west central, central, and northern areas of West Virginia the Pocono is undifferentiated. In Calhoun and Gilmer Counties the Big Injun sandstone is absent, and throughout Braxton, Harrison, Lewis, and Barbour Counties, the Pocono sequence consists of several hundred feet of sandstone, siltstone, and shale interbeds[8]. It is important to note that the thicknesses of the Big Injun in many areas of the state are at best approximate because drillers have commonly misidentified the unit or have not differentiated between sandstones, siltstones, and sandy-shales, recording all three lithologies as sandstone[11].

In east-central West Virginia, in an area including northern Webster County, southern Upshur County, and west-central and central Randolph County, the entire Pocono sequence is absent due to non-deposition or erosion. Here the Greenbrier rests unconformably upon the Upper Devonian Catskill red shales and siltstones.

Source areas for the Pocono Big Injun vary, and northern and west to southwestern sources have been proposed. However, Overbey (1967) suggested that there may have been three to four sources for the Pocono Big Injun. The depositional environment for central counties of the state have been interpreted as drowned river valleys, with aspects of stream channel and estuary deposits, while other areas have been interpreted as fluvial deposits overlain by marine deposits[10].

Although there is some production of oil and gas from the Pocono Big Injun, most of the production reported from the Big Injun in central West Virginia is actually produced from the lower sandy beds of the Greenbrier. Overlying the Pocono Big Injun and its equivalents in the north and the Maccrady Shale in the south is the Middle Mississippian Greenbrier Group (Greenbrier Limestone), referred to as the "Big Lime" by drillers. The group has been divided into a number of formations and members, many of which are identified only in southern and southeastern West Virginia. The Greenbrier Big Injun is the basal sandy, oolitic, dolomitic unit of the Greenbrier Group. Differentiation of the Pocono Big Injun and the Greenbrier Big Injun is a serious problem in central and northern West Virginia because the sandy nature of the Greenbrier Big Injun resembles the sandstones of the immediately underlying upper Pocono Big Injun. However, in southern West Virginia the basal Greenbrier is separated from the Pocono sandstones by the Maccrady formation, and, there, most well records in the southern part of the state properly assign this oolitic, dolomitic unit to the Big Lime[12].

As early as 1910, the basal Greenbrier sandy, oolitic, dolomitic zone was recognized as being separate and distinct from the underlying Pocono Big Injun. Over the years it has been assigned several names by drillers including "Beckett" (Cabell County) and "Rouzer" (Clay County)[9]. Although the term "Big Injun" is commonly used by drillers today, the basal Greenbrier in central and northern West Virginia correlates with and may be more accurately named Loyalhanna. The crossbedded sandy limestone or sandy dolomite unit rests unconformably upon the Pocono Big Injun, is less than 100 feet thick, and has been interpreted as shoreline sands. To the south, the basal oolitic zones are generally younger than the Loyalhanna and are considered to have been deposited around topographic highs on the erosional surface of the Maccrady formation. Overall, the basal Greenbrier unit appears to have been deposited in a shallow water, high energy environment of a transgressing sea[13]. The driller's "Keener" sand refers to a calcareous or dolomitic sandstone that has been variably placed above, within, or below the base of the Greenbrier.

C. Big Lime:

The Middle Mississippian Greenbrier limestone, known as the driller's "Big Lime", is a very thick and lithologically complex unit. In the outcrop of southeast West Virginia it is known as the Greenbrier Group, and has been divided in seven formations, including the widely recognized red Taggard Shale, and the oolitic Union Limestone (see Fig. 1). These units are diverse in character consisting of oolitic, fossiliferous, micritic, or sandy limestones, with interbedded shales providing the basis for the subdivision. All seven Greenbrier formations thin to the north with the lowermost units pinching out. In Randolph County the Greenbrier continues to thin and undergoes a facies change from the oolitic and micritic limestones in the south to a non-oolitic, more clastic limestone northward. North of Randolph County the Greenbrier is not divided and is reduced in rank to the Greenbrier formation. However, three distinct units are recognized: the basal Loyalhanna member, a cross-bedded sandy limestone; a middle red to green shale, tentatively correlated with the widely recognized red Taggard Shale; and an upper fossiliferous limestone. Farther north into Pennsylvania, the Greenbrier passes into the shales and red sandstones of the Mauch Chunk formations. In Ohio and Kentucky the Greenbrier equivalents are the Maxville and Newman limestones, respectively.

Most of the Greenbrier divisions seen in outcrops cannot be recognized in the subsurface in West Virginia. Throughout the north-central portion of the state, a basal sandy limestone is present, which has been called the "Greenbrier Big Injun" by drillers. It has been extensively dolomitized throughout, and becomes increasingly oolitic to the southwest. The unit is less than 60 feet thick and correlates with the Loyalhanna limestone. Lying at various positions within, above, or below this basal member is the very fine to fine-grained, calcareous to dolomitic, lenticular Keener Sand.

Most of the oil and gas production reported from the Greenbrier Big Lime is actually from the Loyalhanna, its equivalent basal oolitic dolomite, and the Keener Sand. The Greenbrier, above these lower productive units, is generally fossiliferous and oolitic. Production from the upper part has been scattered throughout the central and southwestern parts of the state, from Harrison to McDowell Counties. Although most of the production has been gas, some oil has been produced in the central counties[14]. It is also important to keep in mind that names applied to shallow production in West Virginia are those of the driller's, and are sometimes loosely applied. Therefore, productive units may or may not be correlative with the same name in adjacent fields or in other parts of the state.

Reservoir porosities range from 10 to 25 percent, primarily from intercrystalline dolomite porosity and intergranular oolitic porosity. Much of the production appears to be from stratigraphic traps related to permeability pinchouts controlled by the degree and extent of dolomitization[9,13]. Although porosity is fair to good, permeability is typically very low and reservoirs generally require hydraulic fracturing for commercial production. Production trends also appear to follow original depositional patterns paralleling ancient shorelines.

The Greenbrier rests unconformably upon Devonian and Mississippian sandstones and shales. The lower boundary is easily recognized because, with few exceptions, there are no carbonate beds below the Greenbrier. However, in central West Virginia where the Loyalhanna is present, when sand is first encountered after drilling through the thick sequence of the Big Lime carbonates, it is commonly recorded by drillers as being Big Injun. Because the driller's Big Injun includes the Greenbrier Big Injun (Loyalhanna) as well as the clastic Pocono Big Injun, in areas where the Loyalhanna is present the bottom of the Big Lime is sometimes recorded 30 to 100 feet above the bottom of the Greenbrier[8]. The upper contact of the Greenbrier is gradational with the Mauch Chunk Group except along the western margin of the state where basal Pottsville sands rest unconformably upon the eroded surface of the Greenbrier[15].

The Greenbrier is highly variable in thickness. From central to southeast West Virginia the series thickens from 425 feet in Greenbrier County to over 950 feet in Monroe County, to greater than 1300 feet in Mercer County. Lime sedimentation began as the Mississippian Greenbrier sea transgressed from the south and southeast over a broad area that included West Virginia, Pennsylvania, Ohio, and Maryland.' At first, the sea was confined to the southern area, where subsidence was rapid and where over 1000 feet of Greenbrier sediments were ultimately deposited. Later, the transgression spread to the north and west depositing up to 300 feet of sediments. Shallow marine conditions persisted throughout the region, with occasional terrigenous influxes of quartz and clay-rich sediments from the vast lowland that lay to the north and east[13].

Several depositional models have been proposed for the Greenbrier. Northern shoreline sands have also been proposed for the sandy Loyalhanna and Keener units, while the basal oolitic facies formed around topographic highs produced by erosion of the underlying Maccrady formation. During the Late Mississippian, the Greenbrier seas began to retreat and with uplift and renewed erosion in the east, clastic sediments of the Mauch Chunk began to fill the basin.

D. Weir:

The driller's "Weir Sand" is one of several sandstone units within the Lower Mississippian Pocono Group in West Virginia. The Pocono Group contains all the rocks from the top of the Upper Devonian Hampshire formation to the base of the Greenbrier Group, and is composed of predominantly gray siltstones and shales, with several lensing sandstone units. These sandstones are known to drillers as the "Berea", "Weir", and "Squaw" sands, although Williamson[16] identified and correlated up to 14 units within the group in southern West Virginia. The sandstones are very irregular and inconsistent laterally, and cannot be arranged into a consistent series of "sands" at a definite position in the stratigraphic column. Also, to complicate matters, the same stratigraphic sequence is not always present throughout the productive areas, and the names applied to the productive sands are loosely used by drillers. Therefore, the nomenclature for this particular sequence is greatly confused[17,18].

The Weir sand was named when it was found to produce in a well near Weir, Kanawha County, and the sand has been an important producer of oil in Kanawha and Boone Counties. In other areas the Weir produces primarily gas. Weir gas production has been reported from various Pocono sandstones located 40 to 300 feet below the Greenbrier in the southeastern counties of West Virginia. Weir production in Kanawha County is from a group of lenticular sandstones, Boone County reports gas production from three to four sandstones, and Raleigh County wells produce from two sandstones. However, Weir gas found in parts of McDowell County comes from a sandstone in the same stratigraphic position as production from the Big Injun in Wayne and Lincoln Counties. The Weir is also essentially the same unit known as the Broad Ford sandstone in Mercer, Monroe, and Summers Counties[17,19]. Other counties where there is important Weir activity are the north-central counties of Ritchie, Braxton, and Lewis[18].

In southeastern West Virginia, Williamson[16] identified a lower and middle Weir siltstone and the Weir sandstone. The lower Weir is a thin unit and was interpreted to have been deposited as offshore bars. It is present in Kanawha, Boone, and Fayette Counties. The middle Weir, present in Kanawha, Putnam, Lincoln, and Boone Counties, was deposited as offshore bars that built into a barrier bar (stacked upon the lower Weir) as the seas transgressed eastward. The overlying Weir is present over much of southern and central West Virginia and was probably deposited along the eastern margin of the basin. It was formed by a marine-dominated delta carrying sediments from the northeast in Middle Pocono time.

E. Berea:

The Berea sandstone in West Virginia, known as the drillers' "Berea Sand", is defined as the basal sandstone unit of the early Mississippian Pocono Group. It is a persistent sandstone-siltstone unit in the subsurface throughout the western half of the state and extends into eastern Kentucky, eastern Ohio, Michigan, western Pennsylvania, and Virginia. Until recently, the Berea was an important producing unit for high-grade oil and gas in West Virginia. Production has been primarily from two linear sandstone units, the Gay-Fink Channel and the Cabin Creek Channel in the central part of the state, and from marine sheet sands in the western counties. Most of the major reservoirs within these areas have now been depleted, and with the discovery of deeper reservoirs, the Berea is now of secondary importance[20].

Origin of the Berea has been controversial and proposed depositional environments include offshore bars[21], channel sandstones[20], and a combination of deltaic, shoreline, and offshore marine deposits[22]. Also, the Berea throughout the Appalachian Basin is composed of sediments from widely separate sources. A northern source in eastern Canada provided sediments for the Berea in Ohio and western Pennsylvania; an eastern source was responsible for the sediments in West Virginia and Virginia; and northern and southern sources affected Kentucky. Berea sediments were transported into a variety of environments in the Appalachian Basin and coalesced to form a wedge of sediments consisting of the Bedford Shale and the overlying Berea sandstone. These two units are genetically related and represent a regressive-transgressive sequence between periods of quiescence. It is interesting to note that the boundary dividing Berea sediments derived from a northern source from those derived from an eastern source also approximately divides Berea oil production into eastern Pennsylvania grade and western Corning grade oils[22].

The Berea sandstone is present throughout most of the western part of West Virginia. The eastern edge of the Berea apparently abuts against a linear area of Devonian Shales, and along this eastern limit the Berea forms two long, narrow linear bodies of sandstone, parallel to each other, and trending northwest. These sandstones represent channel-fill deposits[20,22]. The northern Gay-Fink Channel is approximately 60 miles long and may extend an additional 19 miles to the east. Its width varies from 1 to 8 miles with a thickness greater than 10 feet. Locally, the channel thickness may exceed 50 feet but commonly averages 20 to 30 feet. A similar channel, the Cabin Creek, is located approximately 50 miles south of the Gay-Fink trend, and extends into Nicholas County. The channel varies from 2.5 to 5.5 miles in width and 15 to 52 feet in thickness. These channel deposits consist of fine-grained to pebbly, poorly sorted, lenticular sandstones. Porosity and permeability are highly variable, with porosity averaging 16 percent. Coarse-grained and pebble zones are irregularly distributed, and are responsible for occassional wells with very large production. West of the channels the main body of the Berea forms a north-south trending thin sheet sand, that extends as a cresent from southwest Pennsylvania, through southeast Ohio, and into western West Virginia. This portion of the Berea consists of siltstones and fine-grained sandstones that were spread along an eastern shoreline as shoreline sands and offshore marine deposits[20,22,23]. In West Virginia, the thickness varies from 0 to 50 feet, averaging 25 feet. The Gay-Fink and Cabin Creek Channels join with the marine sheet sand at a 70 to 90 degree angle.

Although much of the Berea gas production is from the western marine sheet sand facies, the Cabin Creek and Gay-Fink Fields are probably the most well known oil and gas reservoirs. Throughout much of their extent, both of these channels are underlain and laterally enclosed by shale, and it is this type of stratigraphic pinchout that defines the limits of many of the producing fields. Because of this stratigraphic setting and the low percent primary recovery (only 20-25 percent total oil in place), the Berea is one of the most favorable units in the state for secondary recovery by water injection[20].

Methodology

The general methodology to evaluate and identify high potential areas for exploration and development of gas-bearing formations in West Virginia has already been applied and verified for certain gas-bearing formations (i.e., Big Injun, Berea, and Benson). This methodology consisted of data collection, data interpretation, and assessment of various areas for future development through computer generated 2-dimensional and 3-dimensional maps. The generated maps were the quantitative representation of various reservoir parameters such as porosity, gas saturation, open flow potential, and net pay thickness as functions of latitude and longitude. The superimposition of the mentioned 3-dimensional maps of different reservoir parameters provided the basis for ranking the potentially productive areas/counties in West Virginia. Meanwhile, the 2-dimensional maps were utilized to indicate the precise locations within the areas of interest. A similar methodology was employed in this study to identify potential areas amenable to multiple completion through superimposition of the generated maps of Devonian Shale and other gas-bearing horizons. The various steps pertaining to this study are discussed below.

Data Collection:

The formations under investigation in this study are the Devonian Shale and shallow gas-bearing horizons which include Big Lime, Big Injun, Weir, and Berea. The collected data consisted of well logs (FDC/GS, SNP-CNL/GR when available, IL), open flow potential, well location (i.e., longitude and latitude), and production data.

The data collection was limited to gas-producing wells, consequently, no attempts were made to collect data for oil-producing reservoirs. The wells represented in this study were selected in such a fashion as to avoid data-clustering, thus, creating a uniformly distributed sample across each county in West Virginia.

The major sources of data included:

- The Petroleum Information (PI) data base for open-flow potential and well locations coordinates.
- The West Virginia Geologic and Economic Survey for various well logs.
- The Office of West Virginia Oil and Gas Commissioner for production data.

The study area was limited to the Western part of West Virginia as shown in Figure 2.

Data Analysis:

The collected well logs of shallow gas-bearing horizons were analyzed for identification of gas-bearing intervals and delineation of respective values of porosity, water saturation, and, hence, the gas saturation. Equation 1 has directly been employed to establish the above mentioned parameters[24]. The expression for Equation 1 is:

$$S_w = \left(\frac{FR_w}{R_t}\right)^{1/2} \qquad (1)$$

where:

S_w = water saturation
F = formation resistivity factor
R_t = true formation resistivity
R_w = resistivity of formation water

Further experimental work and field tests have indicated a direct relationship between values of porosity and formation resistivity factors as shown:

$$F = \frac{a}{\phi^m} \qquad (2)$$

where:

ϕ = porosity, fractions
a = constant
m = cementation factor

The exact solution to Equation 2 depends upon the type of formation lithology under investigation. Archie and Humble have proposed the following relationships:

$$F = \frac{0.62}{\phi^{2.15}} \quad \text{Humble} \qquad (3)$$

$$F = \frac{1}{\phi^m} \quad \text{Archie} \qquad (4)$$

While the Humble equation is most satisfactory for sucrosic textured carbonate rocks, the Archie relationship yields better results in chalky and carbonate formations[5]. Equations 1 and 3 have been combined for accurate determination of water saturation values and delineation of potential gas-bearing horizons.

Due to the heterogeneous nature of Devonian Shale, no attempts were made to determine porosity and gas saturation values. However, true formation resistivity values were evaluated and utilized for correlation purposes.

Computerized Maps Generation:

The collected and interpreted data were compiled to establish a data base file which was used to plot/generate the 2-dimensional and 3-dimensional maps to quantitatively and qualitatively analyze the compiled data for West Virginia.

A computer program with graphic capability was employed to generate the 2-dimensional and 3-dimensional maps. This program randomly takes (x, y, z) values and creates a mesh on (x, y) plane and establishes (z) value above each point of the mesh. The (x, y) values represent the longitude, latitude (both in degrees) and the (z) value is an optional third variable which may assume the values of open flow potential, porosity, gas saturation, thickness, or the combination of these parameters. Figure 2 illustrates a 3-dimensional grided map of West Virginia. The absence of the anomalies/peaks in this map indicates an input value of zero for the third (z) variable, thus, permitting Figure 2 to serve as a base reference map for this study.

The program requires two fixed parameters which consist of angles of tilt and rotation. These parameters determine the vantage point from which the data is viewed. The angle of rotation is the x-y plane while the angle of tilt represents the x-z plane. For example, Figure 2 was generated at -90° and 0° angles of rotation and tilt, respectively. There are no restrictions on values that the mentioned angles may assume, however, a range of -80° to 80° is recommended for angle of tilt. The maps can be generated on most regular terminals, however, better resolution will be achieved if graphic terminals are employed.

Figure 3 represents the 3-dimensional map of open flow potential for Devonian Shale. The encountered anomalies illustrate the regions/areas of high potential. The precise locations of respective anomalies can be identified by generating a 2-dimensional map as shown in Figure 4. This figure contours open flow potential (any other parameter could have been pre-selected) as a function of longitude and latitude, thus, pinpointing the exact location of high potential areas.

The program which generates the 2-dimensional maps consists of 3 different segments. The first segment of the program converts the longitude and latitude into x-y coordinates. The second segment of the program interpolates the data to generate a matrix of the pre-selected parameter values at the intersection of the horizontal and vertical mesh line over the mapped area. Finally, the third segment of the program connects the parameter values, hence, generating a contour map which is plotted using a graphic terminal.

Discussion

In order to identify the areas with a high potential for gas production in the formations under study, 2-dimensional and 3-dimensional maps of open flow potential, and hydrocarbon potential (porosity x gas saturation x thickness), and production were generated. The hydrocarbon potential maps were only generated for shallow formations while the true formation resistivity map was generated for the shale horizons. Figures 3, 5, and 6 are 3-dimensional maps of open flow potential, true formation resistivity, and production for the Devonian Shale horizons, respectively. These computer generated maps exhibited a direct correlation with one another, however, such a correlation is more evident when dealing with the true formation resistivity and open flow potential maps. Figures 7 and 8 which are computer generated 2-dimensional maps of open flow potential and true formation resistivity further confirm and enhance the existence of the mentioned correlation. Similarly, the generated maps for shallow gas bearing formations (Berea, Big Lime, Big Injun, and Weir) did exhibit a general correlation between hydrocarbon potential and production. Figure 9 represents the computer generated 3-dimensional maps of open flow potential, hydrocarbon potential and production for the Berea sandstone, respectively. The illustrated anomalies/peaks for the hydrocarbon potential and production maps correlate well with one another, while such correlation with the open flow potential is less pronounced.

Production is the final test of a well. Therefore, hydrocarbon potential, which correlates closely with production for all the formations, was used as the parameter for the ranking purposes. This consideration was also based upon the availability of a larger data base on hydrocarbon potential. The production maps of Devonian Shale were used in conjunction with the hydrocarbon potential maps of shallow gas bearing formations to rank the counties for multiple completion. The results are summarized in Tables I and II. Table I is the ranking for the counties which have high potential in Devonian Shale, while Table II is the ranking for counties where the shallow formations have high potential. Figures 10 through 13 exhibit the various possibilities that may occur when multiple completion is employed. It should be mentioned that the results summarized in Tables I and II are relative to the potential contours encountered in the computer generated 2-dimensional map for the Devonian Shale, Figure 14. It must be mentioned that this study can be extended to other shallow gas-bearing horizons in West Virginia and/or to other parts of the Appalachian Basin.

Acknowledgement

The authors would like to extend their thanks and appreciation to Kathy Bruner for doing the detailed literature search pertaining to the formations discussed in this paper.

Conclusions

1. Areas where the Devonian Shale in West Virginia can be successfully developed through multiple completion have been identified and evaluated.

2. Hydrocarbon potential (porosity x gas saturation x thickness) was found to be an additional parameter to identify the high potential areas for gas-bearing horizons.

3. The maps of production, open flow potential, and true formation resistivity of Devonian Shale indicate significant correlations.

4. The methodology can be applied to other areas.

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TABLE I

Counties with Most Potential for Multiple Completions in WV

HIGH POTENTIAL DEVONIAN SHALE

County	Formations
1. Ritchie	BL+BI+W+BR+DS
2. Wood	BI+BR+DS
3. Wayne	BI+DS
4. Pleasants	BR+DS

BL = Big Lime
BI = Big Injun
W = Weir
BR = Berea
DS = Devonian Shale

TABLE II

Counties with Most Potential for Multiple Completions in WV

HIGH POTENTIAL SHALLOW HORIZONS

County	Formations
1. Kanawha	BL+BI+W+BR+DS
2. Boone	BL+BI+W+BR+DS
3. Clay	BL+BI+W+BR+DS
4. Logan	BL+W+BR+DS
5. Raleigh	BL+W+BR+DS
6. Fayette	BL+BI+W+DS
7. Calhoun	BI+W+BR+DS
8. Lincoln	BL+BI+BR+DS
9. Roane	BI+W+BR+DS
10. Wirt	BI+W+BR+DS
11. Mingo	BI+BR+DS
12. Putnam	BR+DS
13. Jackson	BR+DS

BL = Big Lime
BI = Big Injun
W = Weir
BR = Berea
DS = Devonian Shale

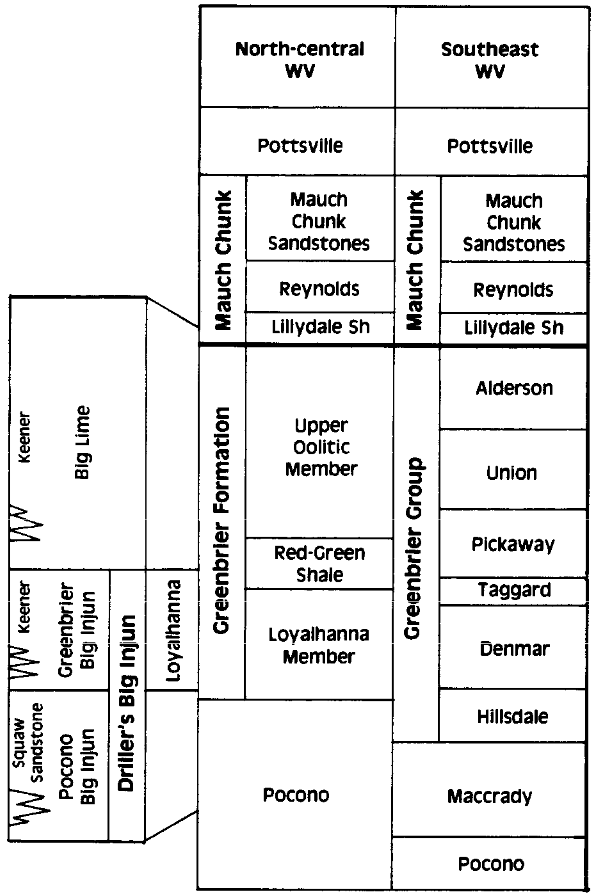

Fig. 1—Geological units within the scope of study.

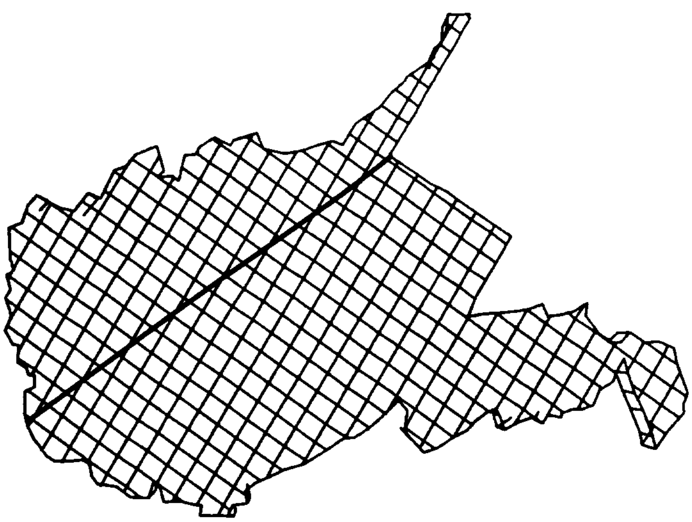

Fig. 2—West Virginia reference map.

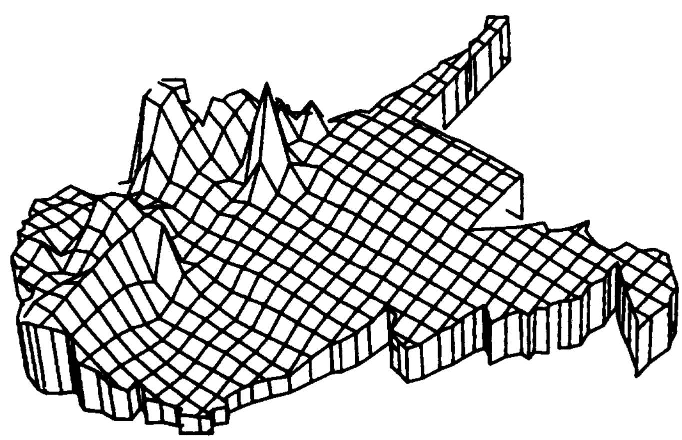

Fig. 3—Three-dimensional map of open-flow potential for Devonian shale.

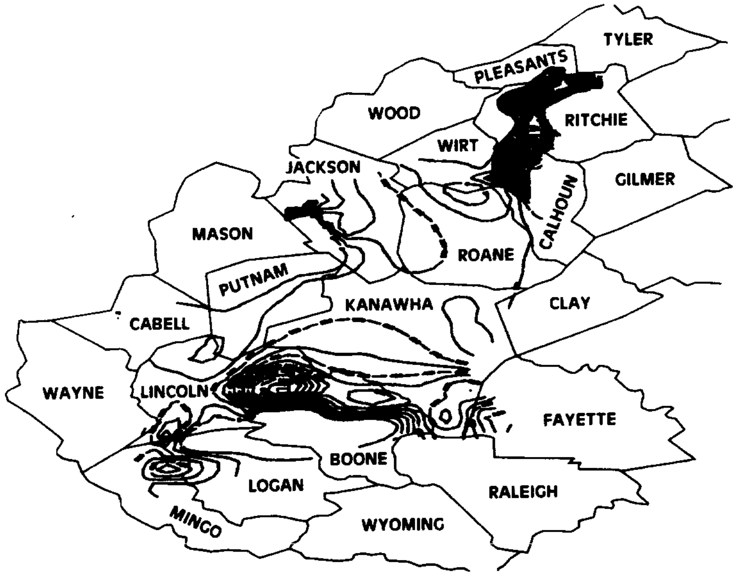

Fig. 4—Two-dimensional map of open-flow potential for Devonian shale.

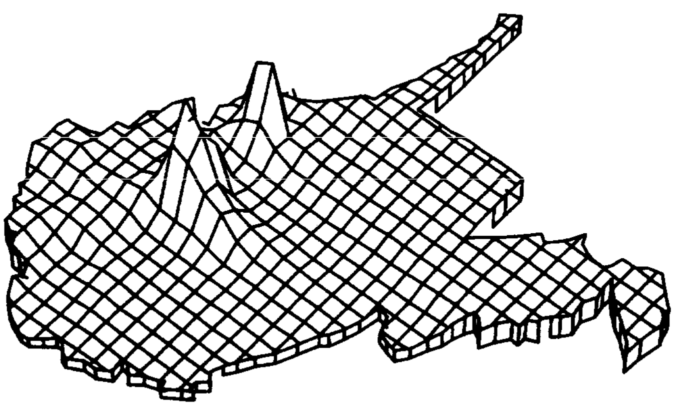

Fig. 5—Three-dimensional map of true formation resistivity for Devonian shale.

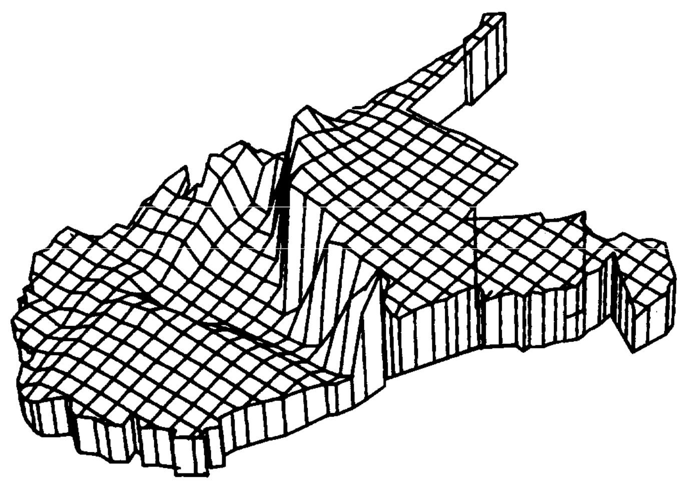

Fig. 6—Three-dimensional map of production for Devonian shale.

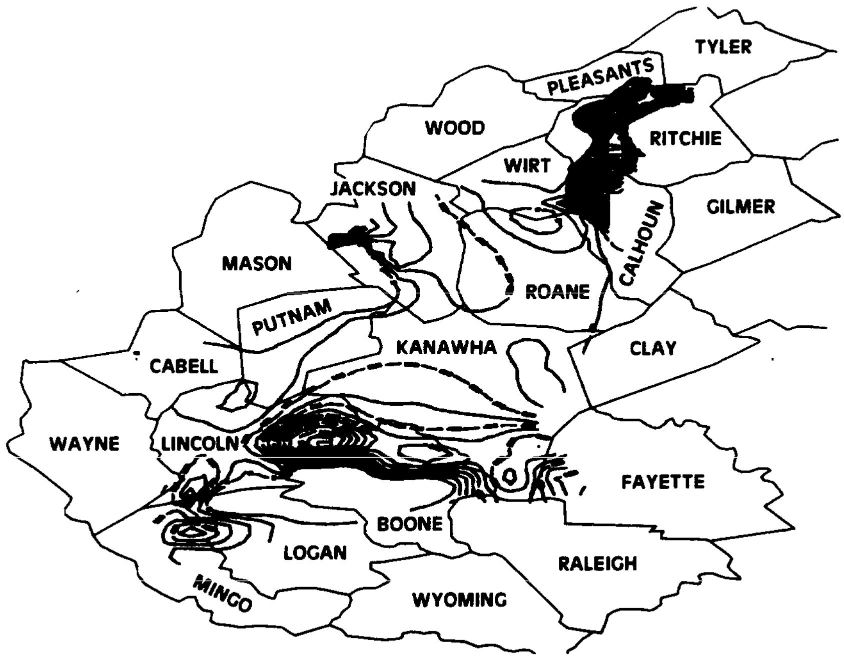

Fig. 7—Two-dimensional map of open-flow potential for Devonian shale.

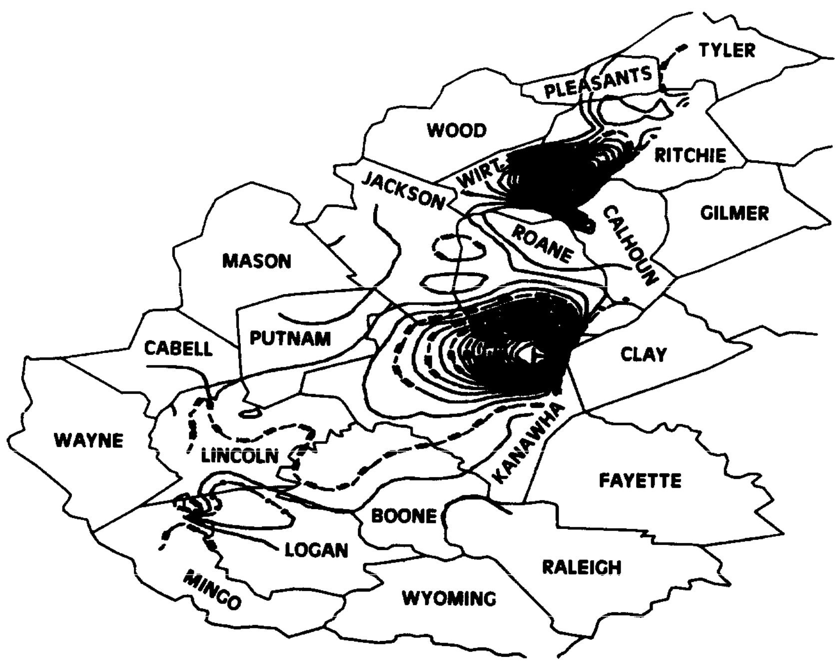

Fig. 8—Two-dimensional map of true formation resistivity for Devonian shale.

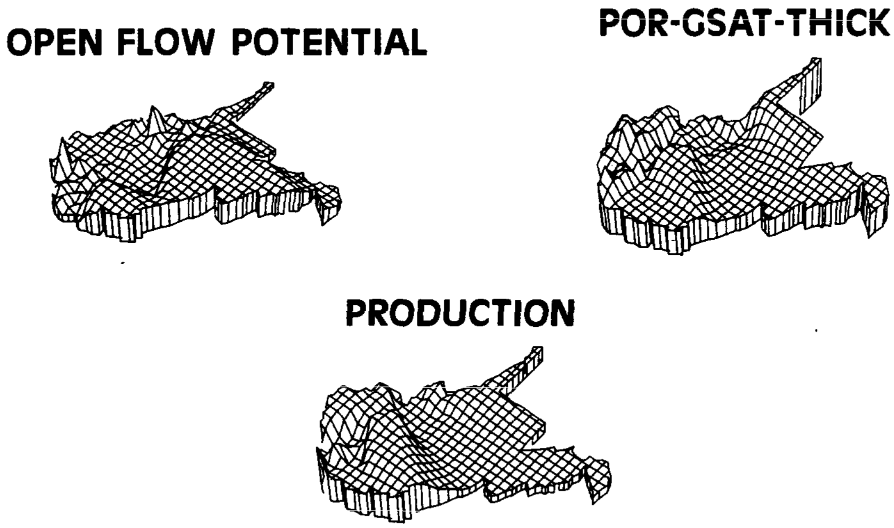

Fig. 9—Three-dimensional maps of various parameters for Berea formation.

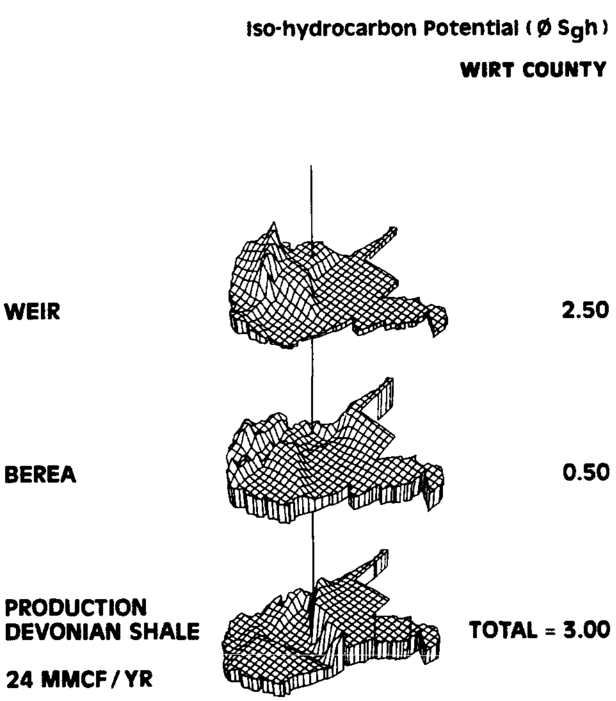

Fig. 10—Multiple completion, Wirt County, WV.

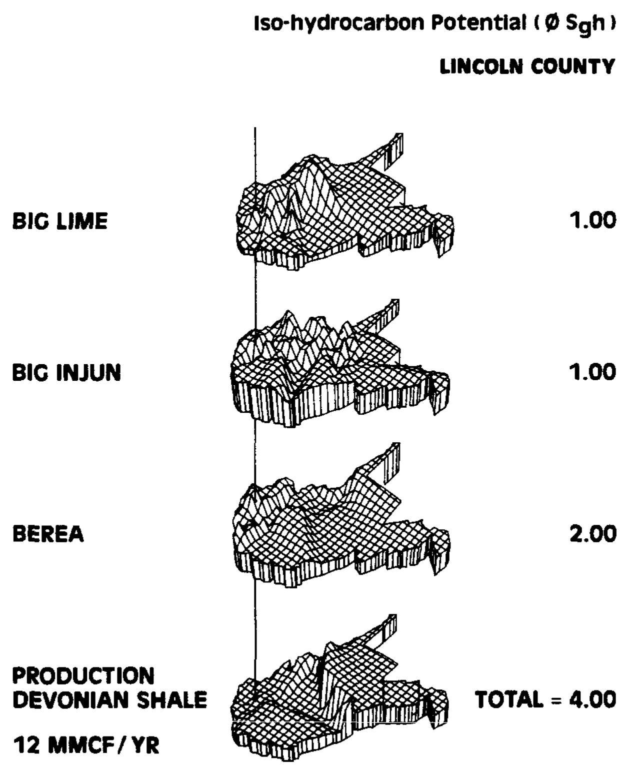

Fig. 11—Multiple completion, Lincoln County, WV.

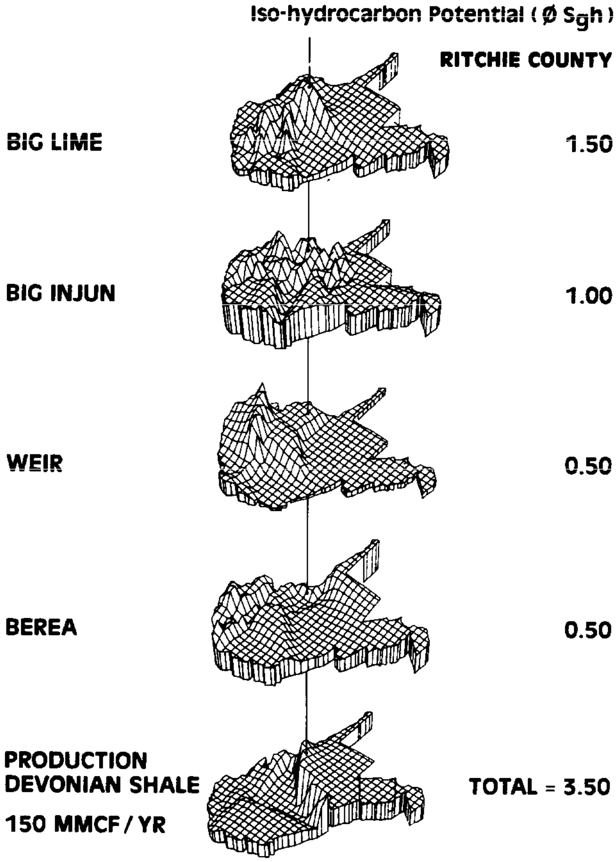

Fig. 12—Multiple completion, Ritchie County, WV.

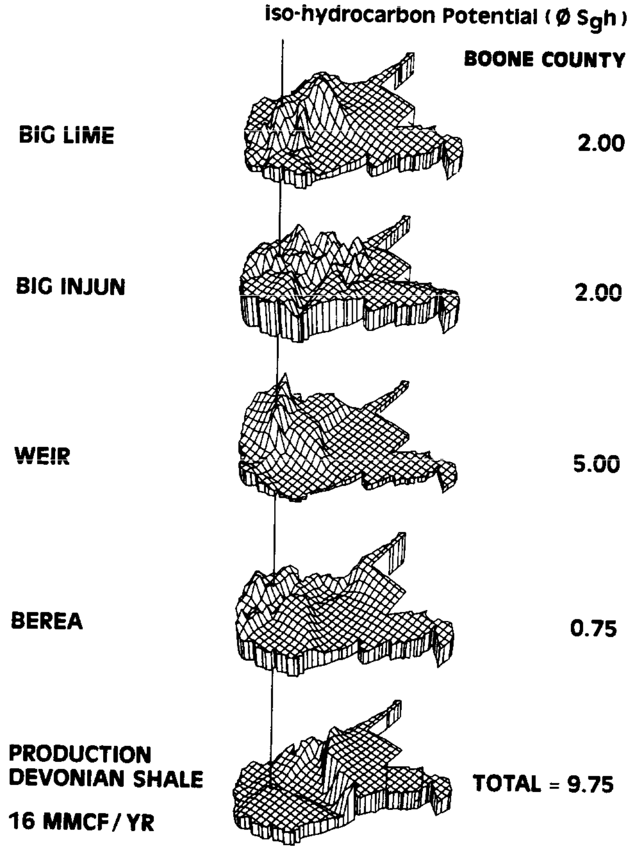

Fig. 13—Multiple completion, Boone County, WV.

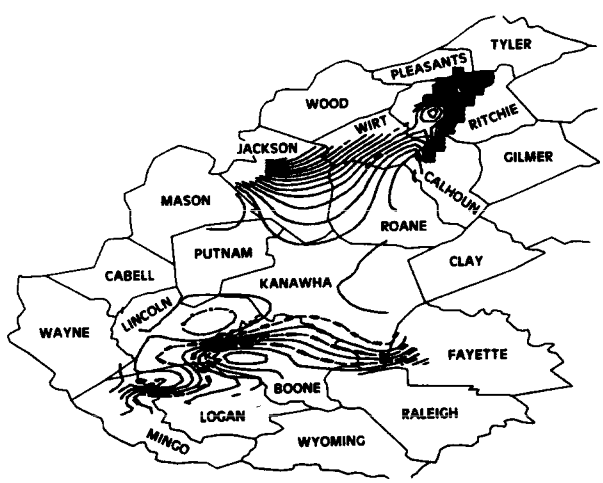

Fig. 14—Two-dimensional map of production for Devonian shale.